Module 2: Basic Principles of Energy

Learning Objectives

After completing this module, you will be able to
- Define energy in its various forms and energy related properties;
- Use the correct units for energy and power, and convert from one unit to another as needed;
- Determine the properties of steam and moist air;
- Describe the mechanisms by which heat is transferred;
- Explain the effect of insulation on heat transfer, and the means by which radiative heat transfer is controlled.

2.1 Energy and Its Various Forms

Energy is very simply defined as *the ability to do work*. In technical terms, work is defined as force applied through displacement (the vector equivalent of distance):

$$W = F \times d$$

Energy can take many different forms and do many different types of work. One very important law of nature, which guides the process of energy management, is that energy cannot be created nor destroyed, only converted from one form to another. The forms of energy discussed in this Guidebook include chemical energy, nuclear energy, thermal energy, mechanical energy, and electrical energy.

2.1.1 Chemical Energy

Chemical energy is the energy which helps to "glue" atoms together in those clusters called *molecules*, or *chemical compounds*. Of special interest to us are substances such as natural gas, or propane, or oil that are capable of releasing some of that energy. When we burn these fuels, we unglue some of the atoms from each other, liberating the chemically-bound energy that held them together. In the process, the chemical energy is changed in form to high temperature heat energy, a form well suited to doing many different kinds of work. This process takes place every time we flick a butane lighter.

2.1.2 Thermal Energy

Thermal energy involves the microscopic movement of atoms and molecules in everything around us. Thermal energy is often commonly referred to as heat. In fact, there are really two types of thermal energy.

- **"Sensible" Energy** or sensible heat, is energy that jostles molecules and atoms in substances such as water. The more movement, the hotter the substance becomes. Sensible energy gets its name from the fact that we can sense it, by touching the substance directly or indirectly with a thermometer of some type.

  When we add heat to water in a kettle, we increase its temperature.

- **"Latent" Energy** or latent heat, is the energy that is needed to make a substance such as water (a liquid) change to a different form (or phase) of the same substance such as water vapour (a gas). The change of form happens when enough sensible heat is added, and the molecules move too fast to be connected together and eventually separate. It gets its name from the fact that it lies hidden or latent, until the conditions are suitable for it to emerge.

If enough heat is added to liquid water 100^{o}C, it eventually boils and becomes a vapour, also called a gas. If enough heat is removed from liquid water at 0^{o}C, it eventually turns into the solid we call ice. Heat will always naturally flow from a higher temperature to a lower temperature.

Thermal energy may move in many different ways, between many different substances, and change back and forth between its sensible and latent forms. Throughout this guide, much of the discussion is concerned with understanding and managing every form of energy, its movement and transformations.

2.1.3 Mechanical Energy

Mechanical energy is the energy of physical movement, such as moving air or water, a ball being thrown, or even a person sanding a piece of wood. As with many forms of energy, mechanical energy eventually ends up being released or lost as thermal energy. A good example of this is the way that the sandpaper and wood convert mechanical energy to sensible energy that you feel as heat.

2.1.4 Electrical Energy

Electrical energy involves the movement of electric current through wires. Electrical energy is a very useful form of energy because it can perform many functions. Ultimately, most electrical energy or electricity also ends up as thermal energy in the form of sensible heat. Some devices such as electric heaters convert the energy directly; other devices such as motors convert electricity to mechanical energy which eventually becomes heat. The trick to optimizing electricity use is to maximize the amount of work done by electricity before it is lost as heat. Typically, this also involves optimizing the use of mechanical energy.

2.2 Units of Energy

The basic unit of energy in the metric system is the joule. Energy in the form of electricity is given units of watt-hours. The prefix “kilo” indicates 1000 units.

Common equivalencies between units are:

Energy Equivalents	
1000 joules (J)	1 kilojoule (kJ)
1 kilowatt-hour (kWh)	3,600,000 J or 3.6 MJ

2.3 Electricity Basics

2.3.1 Power

Power is the rate of energy flow, or **how fast** energy is being used or transferred. Power is measured in joules per second (J/s). One joule per second is equivalent to one watt. Mechanical power is usually measured in kilowatts in the metric system and horsepower in the Imperial system. Some useful power unit equivalents are:

Power (Energy Rate) Equivalents	
1 kilowatt (kW)	1 kilojoule/second (kJ/s)
1 horsepower (HP)	746 watts (0.746 kW)

The capacity of a boiler is often rated in terms of “boiler horsepower”. 1 boiler horsepower is equal to 9809.6 watts. This should not be confused with the unit of mechanical power also called horsepower.

The information presented here is limited to the concepts necessary for understanding the topics to follow in subsequent sections.

2.3.2 Definitions and Units

The electrical power or demand used in a circuit depends on two fundamental quantities, *voltage* and *current*:

1) *Voltage* is the magnitude of the driving force that sends electrical charge through a conductor (similar to pressure in a water distribution system or the force applied by a man pushing a child on a swing). Voltage is measured in volts.

2) *Current* is the rate of flow of charge through a wire caused by the push of the voltage (similar to the rate of flow of water through a pipe or the speed of the child being pushed on a swing). Current is measured in amperes (amps).

3) *Power* is voltage and current acting together to do useful work. Power is measured in watts. Mathematically, the relationship is represented as:

$$\text{Power} = \text{Voltage} \times \text{Current}$$

$$\text{Watts} = \text{Volts} \times \text{Amps}$$

4) *Demand* is the rate of use of electrical energy. The term “demand” is essentially the same as electrical power, although demand generally refers to the average power measured over a given time interval. *Peak Demand* is the maximum demand experienced over a given time interval, and is especially important in the way we purchase electricity.

2.3.3 Alternating Current and Power Factor

Direct Current (DC) is an electric current that always flows in the same direction, as you would find in the electrical system in a car.

In DC circuits, Power is always equal to Volts x Amps, because the voltage (push) and current (flow) always work together.

Alternating Current (AC), as its name implies, changes direction periodically, reversing its flow on a regular basis (switching from push to pull). AC is used by utilities to transmit and distribute electricity because it is safer and easier to control.

The typical supply voltage goes through a complete cycle 50 times per second, known as 50 Hertz or Hz. When it does this it swings from +310 Volts to **-** 310 Volts. This results in a root mean square (RMS) average voltage of 220 Volts:

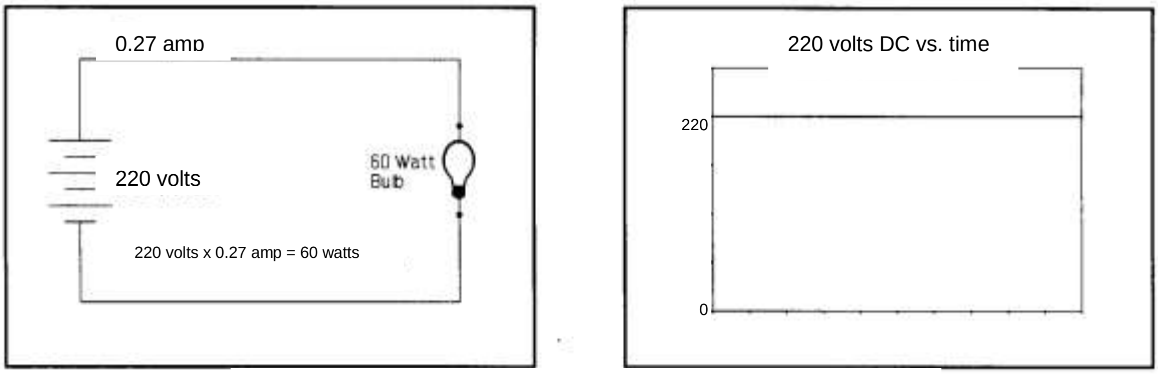


Figure 2.1: A DC Circuit and Waveform

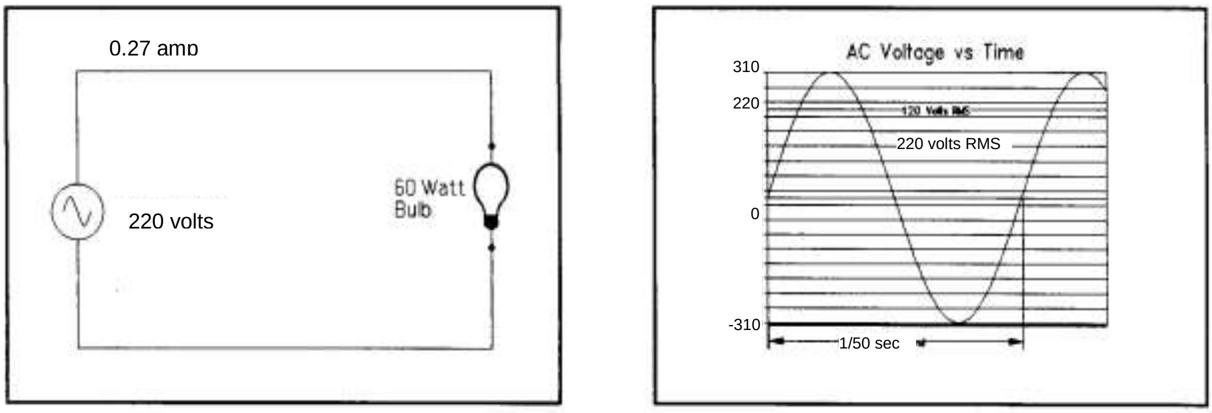


Figure 2.2: An AC Circuit and Waveform

In AC circuits, the current and voltage do not always work together. How well they work together is represented by the Power Factor (P.F.), a number from 0 to 1 or 0 to 100%. Using the analogy of a man pushing a child on a swing, if he pushes the swing at the very top of the swing cycle, he gets the maximum benefit of the push (100% P.F.). If the push is done at a point less than the top of the cycle, some of the push is lost, and the power factor is less than 100%.

2.3.3.1 Things That Affect Power Factor

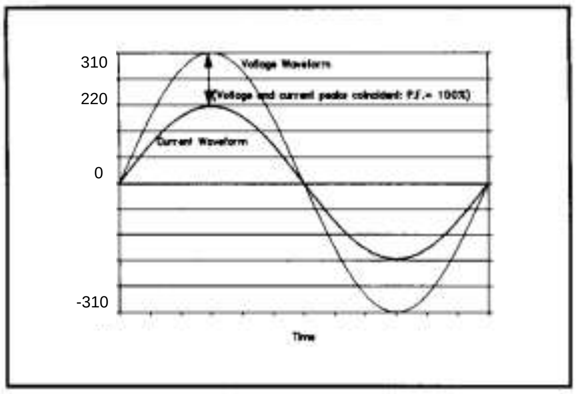
- Electric heaters and incandescent lamps are called **Resistive Loads**. These loads do not reduce power factor. They allow the voltage and current to work together at 100% PF.

- Motors, transformers and loads with coils are called **Inductive Loads**. These cause the current to slow down. The power factor for such devices could range from 0 to 100%.

- There are devices designed to counteract the effect of inductive loads. These are called **Capacitive Loads**, and the devices are called capacitors. These devices consist of wires or metal plates separated by an insulating material and they cause the voltage to slow down. The power factor could range from 100% to 0.

Since Capacitive and Inductive loads counter each other, a technique called Power Factor Correction utilizes this principle by adding capacitors to a circuit to move its power factor closer to 100%.

Graphically, resistive and inductive circuit waveforms are represented in Figure 2.3.



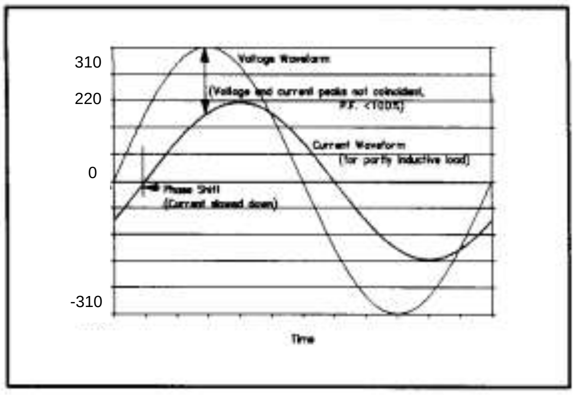


Figure 2.3: Waveforms Illustrating Power Factor

2.3.3.2 The Basic Arithmetic for Power Factor

The relationships between Power, Current, Voltage and Power Factor in AC circuits can be summed up by these equations:

$$Kilowatts\ (kW) = \frac{Volts\ x\ Amps\ x\ PowerFactor}{1000}$$

If we ignore the effect of power factor, and simply multiply the voltage by the current in an AC circuit, the result is called VoltAmps, or, in multiples of 1000, kiloVoltAmps. The formula for this is:

$$Kilovoltamps\ (kVA) = \frac{Volts\ x\ Amps}{1000}$$

$$Kilowatts\ (kW) = kVA\ x\ Power\ Factor$$

We can therefore conclude that the kilowatts and the kiloVoltAmps are related by the power factor: And finally, if we know both the kilowatts and the kiloVoltAmps we can calculate the power factor:

$$PowerFactor = \frac{kW}{kVA}$$

Note the use of the prefix "kilo" meaning "1000's of", since this is the most common multiple used when dealing with power. (At the utility level, it is also common to use "mega", meaning 10^6.)

The most important concept here is that kVA is either equal to kW (in the case of a purely resistive load), or greater than kW (in the presence of inductive loads, i.e. motors and transformers). If the facility is metered in kVA, as is usually the case in South Africa, the difference will cost money. Therefore, controlling the power factor will bring the kVA closer to the kW and save money.

2.3.3.3 Power Factor Correction

As noted above, electrical demand is normally billed on the basis of kVA; the "useful" electrical power is kW, which is always less than or equal to kVA in accordance with the power factor relationship. If power factor is less than about 96%, there is usually an economic case for power factor correction.

Power factor is increased by adding electrical capacitance to the electrical distribution system, either at the inductive load that is influencing overall PF adversely, or as an addition to the entire system. Most often, power factor correction is applied as a passive system, consisting of a specific total capacitance either at the load or at the service entrance to the system. Tables and design methods exist to enable the electrical engineer to determine the capacitance required to bring system power factor to the desired level. From the audit point of view, it is a simple calculation to estimate the savings that will accrue from the correction system, savings against which the cost of implementation can be compared.

For customers billed on kVA demand there is an opportunity to reduce the peak or maximum kVA demand by increasing the power factor. As seen above, power factor is the ratio of real power in kilowatts (kW) to the apparent power in kilovoltamps (kVA). With the application of a capacitor or bank of capacitors it is possible to reduce the kVA demand while maintaining the real power consumption, the kW demand.

- **Correct power factor**
  In practice it is only the on-peak power factor that really is of concern from the perspective of demand costs.

- **Correct power factor at service entrance**
  This can be done with the addition of a fixed capacitor bank provided that the load and power factor are constant. Otherwise a variable bank (one that adjusts itself to the load and power factor) will be required.

- **Correct power factor in the distribution system**
  When large banks of loads are switched as a unit within the distribution system, installing capacitors at the point of switching may be an advantage. This has an added secondary benefit in that it may also free up current carrying capacity within the distribution system.

- **Correct point-of-use power factor**
  When a large number of motors start/stop frequently or are only partly loaded, it may be operationally advantageous to install power factor correction capacitors at the point-of-use (i.e. at the motor). In this manner the correction capacitors are brought on-line with the motor and removed as the motor is stopped.

2.3.4 Electrical Energy

In the previous section, we talked about electric power. When power is consumed for any period of time, energy is used. Energy consumption is the total amount of electricity consumed over time and is measured in **kilowatt hours** (**kWh**). By definition:

Energy = Average Demand x Time

The kilowatt-hour is the unit of energy:

kilowatt hours = kilowatts of demand x hours of consumption

2.4 Thermal Energy Basics

Thermal energy is stored and transferred in a variety of ways. This section provides an introduction to the basic concepts.

2.4.1 Temperature and Pressure

Temperature and pressure are measures of the physical condition or state of a substance. Typically, they are closely related to the energy contained in the substance. As a result, measurements of temperature and pressure provide a means of determining energy content.

2.4.1.1 Temperature

The “temperature” of a substance is a measure of the amount of energy involved in the movement of the molecules and atoms, or the sensible heat content of a substance. In the Celsius scale the freezing point of water is $0^{O}C$ and the boiling point of water is $100^{O}C$.

Temperature may be measured in many different ways. A mercury or alcohol thermometer (in which a fluid expands as it warms) is the most common. Other devices such as a "thermocouple" produce an electrical voltage that is proportional to the temperature, or change their electric resistance with temperature.

2.4.1.2 Pressure

Pressure is the push exerted by a substance upon its surroundings. The molecules in air move because of their energy. We can increase the amount of movement of the molecules by adding sensible energy or heat to a gas. When we heat a gas in a confined space, we create a pressure increase, or more push. For example, heating the air inside a balloon will cause the balloon to stretch as the pressure increases.

Pressure, therefore, is also indicative of stored energy. Steam at high pressures contains much more energy than at low pressures. Gauge pressure is defined relative to the prevailing atmospheric pressure (101.325 kPa at sea level), or as absolute pressure:

Absolute Pressure = Gauge Pressure + Prevailing Atmospheric Pressure

SI Units of measure of pressure: kilopascals (kPa)

2.4.1.3 Thermal Energy Units of Measure

Thermal and electrical energy units can be inter-converted. The basic unit of thermal energy is the Joule (J) defined as the work done (or mechanical energy required) when a force of 1 Newton is applied through a distance of 1 metre. Because the Joule is relatively small, we usually speak of megajoules (MJ – 10^6 joules) or gigajoules (GJ - 10^9 joules).

The delivery of 1 J/s is equivalent to 1 watt. It can then be calculated that
1 kWh = 3.6 MJ.

2.4.2 Heat Capacity

In many everyday situations, we move thermal energy from one place to another by simply heating a substance, and then moving that substance. A good example is a hot water heating system in a home or office building. Heat is moved from the boiler to the room radiator by heating water at the boiler and then pumping it to the radiator where it heats the room. Water is frequently used because it has a good capacity to hold heat.

The specific (i.e. per unit mass) heat capacity of a substance is defined as the amount of heat required to raise 1 kilogram of the substance by 1 ^{O}C. The units of measure are kilojoules per kilogram per degree Celsius. Typical specific heats are listed below.

Substance	Heat Capacity
Water	4.19 kJ/(kg^{O}C)
Ice	2.04 kJ/(kg^{O}C)
Aluminum	0.912 kJ/(kg^{O}C)
Brick	0.8 kJ/(kg^{O}C)

Usually the heat capacity of a substance is known and the question is how much heat is required to raise its temperature a certain amount or how much heat it contains. A very simple formula can be used to calculate this (units are shown in brackets):

Heat (kJ) = Mass (kg) x Specific Heat Capacity (kJ/kg^{O}C) x Temperature Change (^{O}C)

Or

$$Q = M \times C \times (T_2 - T_1)$$

This is a very useful formula in energy management. Thermal energy is often transferred via the flow of water, air, or other fluid. This formula, or one based on it, may be used to calculate the energy flow that is associated with this mass flow.

2.4.3 Sensible and Latent Heat - A Closer Look

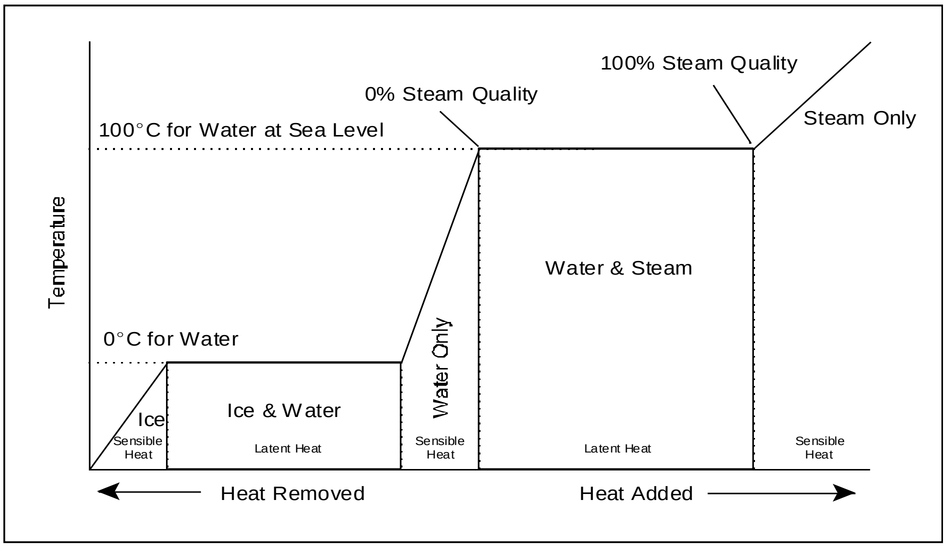


Figure 2.4: Phase Changes for Water

Sensible heat cannot be added to a substance without limit. For any given substance there is a point that if we added enough heat, the form of the substance changes. Putting this another way, at a certain temperature the movement of the molecules that make up the substance becomes so great that the form of the substance changes. This is what happens when ice is heated: eventually it melts and becomes liquid water. Again, at 100^{O}C, water gets so agitated that it becomes water vapour. This is illustrated in Figure 2.4

Starting at the bottom left on the chart, as heat is added, the temperature of the ice increases according to its capacity to hold heat.

At $0^{O}C$, the temperature stops rising, but heat is still being added. Eventually, all the ice turns to water and the temperature starts to rise again. The heat added to melt the ice is called the **latent heat of melting or fusion.**

As more heat is added, the temperature of the water rises. The sensible heat in the water increases. But eventually the water cannot hold any more sensible heat, and the temperature once again reaches a plateau. Now water is being converted to water vapour. Heat is added and absorbed until all the water becomes a vapour. The total amount of heat absorbed and hidden in the vapour on this plateau is called the **latent heat of vaporization**. Finally when enough heat is added, and all the water is converted to vapour, the water vapour begins to absorb sensible heat and its temperature starts to rise again.

Looking at the increase in temperature, we can make some observations:

- The ability of the ice (solid), water (liquid) or vapour (gas) to absorb heat is called its heat capacity and this determines the rate of the temperature increase on the sloped sections of the chart. The higher the heat capacity of the substance, the less steep is the slope. The lower the heat capacity, the faster its temperature rises, and the greater the slope.

- The amount of heat that lies latent or hidden in the liquid or vapour is indicated by the length of the plateau sections. The longer the plateau, the greater the latent heat. The latent heat that is stored in water vapour is much greater than that of the liquid water. That is the reason that steam is so useful in thermal energy systems, it holds a lot of energy. The latent heat of vaporization is 2256.9 kJ/kg at $100^{O}C$ and 101.325 kPa absolute pressure.

2.4.3.1 Evaporation

Evaporation is the process through which a substance in its liquid form changes state to a vapour or gaseous form. This is achieved by adding heat as described above.

2.4.3.2 Condensation

Condensation is the process through which a substance in its gaseous state changes state to the liquid form. This is achieved by cooling the substance. When the change of state occurs, the latent or hidden heat is released.

2.4.3.3 Steam

The term *steam* often refers to a mixture of water and vapour. Strictly speaking, steam is water vapour At the beginning of the vaporization plateau there is 0% vapour and 100% water. At the end of the plateau, there is 100% vapour and 0% water. In the middle, there is 50% vapour and 50% water. The water in the middle may be in the forms of very small droplets, just like fog. Steam quality, indicated as a percentage between 0% and 100%. is simple a reference to the proportion of vapour in the steam.

Steam has many properties which have been extensively studied and tabulated. Steam tables provide values for the energy content of steam at various conditions.

Typical units related to steam measurement are:

Conditions:	**Temperature (^{O}C) and Pressure (kPa)**
Mass:	**kilograms (kg)**
Mass Flow:	**kilograms per hour (kg/hr)**
Energy Content:	**kilojoules per kilogram (kJ/kg)**

2.4.3.4 Moist Air and Humidity

Another very common form of latent heat encountered in a facility's systems is that which is contained in moist air. When it rains or it is very foggy, there is moisture in the air. In fact, when it rains, the moisture in the air has just changed from a vapour to a liquid. The dew on the grass in the morning has formed because of the same process, the process of condensation.

The fact that air is moist has two important implications for the heating and cooling of air:

- Air that is moist has a greater heat capacity; thus, if we are going to heat it, we will need more heat.
- If we reduce the temperature of the air, we may reach a temperature at which the water vapour turns to liquid, releasing its latent energy and making it more difficult to cool the air than if the water vapour was not there. Condensation makes it harder for an air conditioner to cool air, for instance.

The amount of moisture or water vapour contained in air is expressed as its humidity. Absolute humidity is the mass of water vapour per unit mass of dry air. Relative Humidity (RH) given as a percentage, is the actual water content of the air divided by the maximum moisture content of the air at the existing temperature—its humidity at saturation. Relative humidity is always associated with a temperature as measured by a dry sensing element. For example, the relative humidity of air might be given as 65% at 20^{O}C dry bulb.

A psychrometer is used to measure the relative humidity by comparing the temperature sensed by a dry bulb and one completely enclosed by saturated wick. At 100% RH, both bulbs should read the same temperature.

The properties of moist air are presented on a **psychrometric chart**; such as the one included in the **Appendix**.

Measures and units of humidity are:

Humidity Factor	**grams of water per kilogram of dry air (g/kg)**
Relative Humidity	**percentage (%) at temperature (^{O}C)**

2.4.4 Useful Thermal Energy

Given our original definition of energy as the ability to do work, we can say that thermal energy is useful if it can do some thermal work for us. To do so, we must first understand what useful thermal work is.

Some simple forms of useful thermal work might be:

- heating a tank of cold liquid with an electric heater
- heating a vat of chemicals with steam to sustain a chemical reaction
- heating a building in winter with a hot radiator
- evaporating water from milk with a steam coil

The one thing each of these processes has in common is that heat is being added, through the use of a device or fluid that is 'hotter' or at a higher temperature than the original substance. So, in very simple terms, we could associate the ability to do useful work with an increased temperature.

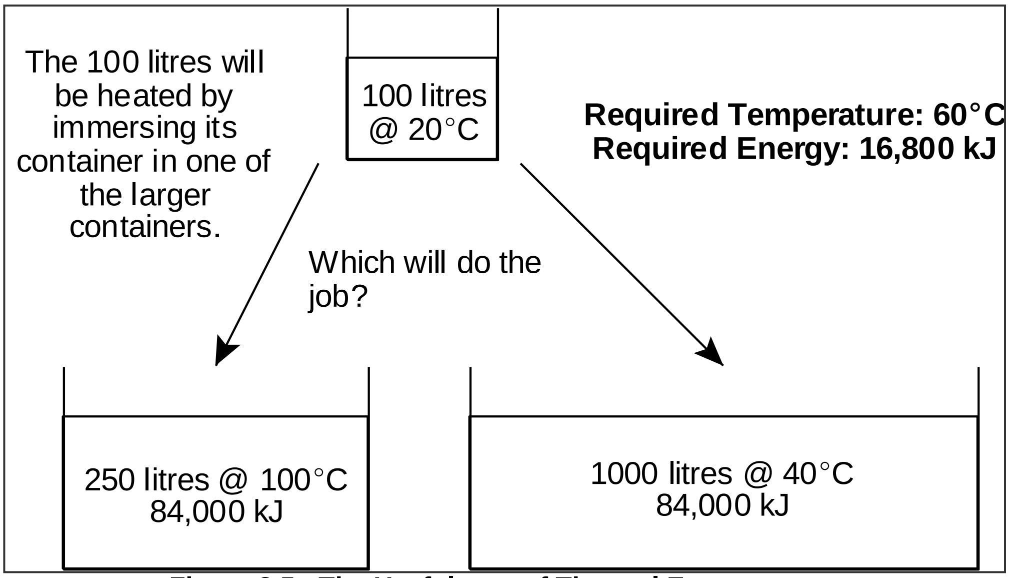


Figure 2.5: The Usefulness of Thermal Energy

Consider the question posed by Figure 2.5. Which container has the greater ability to do work for us if we want to heat 100 litres of water by from 20°C to 60°C by immersing the 100 litre container in one of the other containers.

If the heat capacity of the water is 4.2 kJ/kg, we will need 16,800 kJ of heat. Should we use 1000 litres of water at 40°C, which contains 84 000 kJ of heat more than 1000 litres of water at 20°C? Or, should we use 250 litres at 100°C, which has 84 000 kJ more energy than 250 litres of water at 20°C?

Both contain the same energy, the same amount of sensible heat compared to water at 20°C, far more heat than is required. But, can both do the amount of useful work necessary? No, the larger volume of water will never be able to raise anything above it's own temperature of 40°C. The heating source must be hotter than the 60°C we want to achieve. Therefore, we conclude that we need the 250 litres of water at 100°C.

The ability to do work is not related only to the quantity of energy contained in a substance, but also to the temperature of that substance. Another way to think about this is that heat and thermal energy will only flow "downhill" from higher to lower temperature. Much of thermal energy management is concerned with manipulating temperatures to get the maximum amount of useful work from thermal energy or heat that we have purchased.

In the case of latent energy, the ability to do useful work is accessed through phase changes, but the temperature of the phase change does not indicate how much energy is available

The usefulness of sensible energy is indicated by the temperature of the substance possessing the energy compared to the surrounding temperatures.

2.5 Heat Transfer - How Heat Moves

The transfer of thermal energy or heat is driven by a temperature difference. The rate at which heat moves from a high temperature body to a body at a lower temperature is determined by the difference in temperatures and the materials through which the heat transfer takes place.

There are three fundamental processes by which heat transfer takes place. These are **conduction**, **convection** and **radiation**. All heat transfer occurs by at least one of these processes, but typically, heat transfer occurs through a *combination* of these processes. All heat transfer processes are driven by temperature differences, and are dependent on the materials or substances involved.

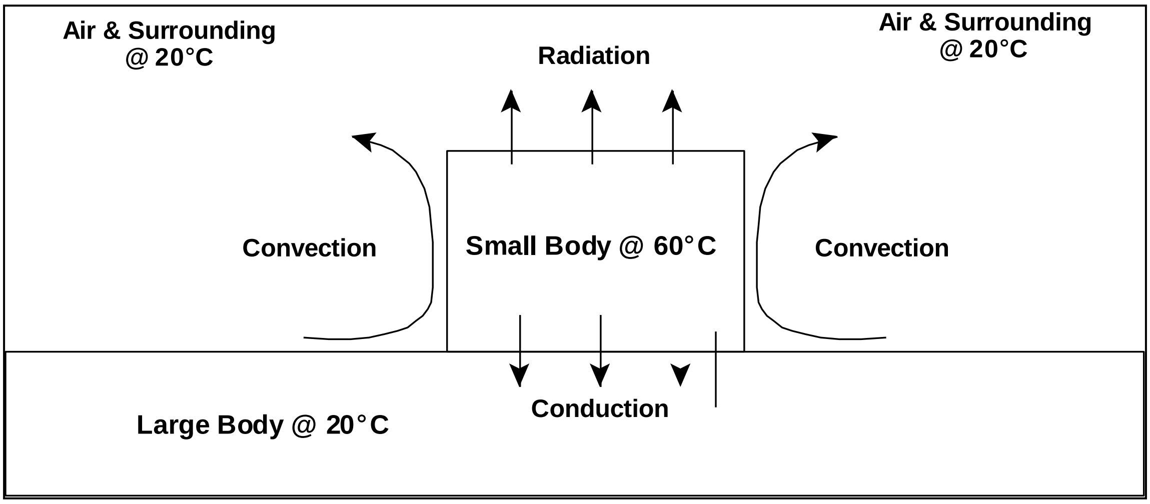


Figure 2.6: The Basic Heat Transfer Processes

Figure 2.6 shows each of these heat transfer processes at work upon a block at 60^{O}C, sitting on and in contact with a cool surface at a temperature of 20^{O}C, surrounded by air at 20^{O}C, and in a room with walls at 20^{O}C.

2.5.1 Conduction

Conduction of heat takes place when two bodies are in contact with one another. If one body is at a higher temperature than the other, the motion of the molecules in the hotter body will agitate the molecules at the point of contact in the cooler body and increase its temperature.

In Figure 2.6, heat will flow by conduction to the material the block is sitting on until the block and the cool surface reach the same temperature. This means that the block will cool and the surface of the large body will warm.

The amount of heat transferred by conduction depends upon the temperature difference, the properties of the materials involved, the thickness of the material, the surface contact area, and the duration of the transfer.

Good conductors of heat are typically substances that are dense as they have molecules close together. This allows the molecular agitation process to permeate the substance easily. So, metals are good conductors of heat, while gaseous substances, having low densities or widely spaced molecules, are poor conductors of heat. Poor conductors of heat are usually called *insulators*.

The measure of the ability of a substance to insulate is its thermal resistance. This is commonly referred to as the *R-value* (RSI in metric). The R-value is generally the inverse of the thermal conductivity, the ability to conduct heat.

Typical units of measure for conductive heat transfer are:
Per Unit Area (for a given thickness): Watts per square meter (W/m^2)
Overall: Watts (W) or kilowatts (kW)

2.5.2 Convection

The transfer of heat by convection involves the movement of a fluid such as a gas or liquid. There are two mechanisms of convection: *natural* and *forced*.

In case of *natural convection*, the fluid in contact with or adjacent to a high temperature body is heated by conduction. As it is heated, it expands, becomes less dense and consequently rises. This begins a fluid motion process in which a circulating current of fluid moves past the heated body, continuously transferring heat away from it. In Figure 2.6 natural convection takes place on the sides and top of the body.

Natural convection helps to cool your coffee in a mug and to bake a cake in an oven.

In the case of *forced convection*, the movement of the fluid is forced by a fan, pump or other external means. A centralized hot air heating system is a good example of forced convection.

Convection depends on the thermal properties of the fluid as well as surface conditions at the hot body and other factors that affect the ability of the fluid to flow. With a low conductivity fluid such as air, a rough surface can trap air against the surface reducing the conductive heat transfer and consequently reducing the convective currents. Fibreglass wall insulation employs this principle. The fine glass mesh is designed to minimize convection currents in a wall and hence reduce convective heat transfer. Materials with many fine fibres impede convection; while smooth surfaces promote convection.

Units of measure for rate of convective heat transfer are: Watts (W) or kilowatts (kW)

2.5.3 Thermal Radiation

Thermal radiation is a process in which energy is transferred by electromagnetic waves similar to light waves. These waves may be both visible (light) and invisible. A very common example of thermal radiation is a heating element on a stove. When the stove element is first switched on, the radiation is invisible, but you can feel the warmth it radiates. As the element heats, it will glow orange, and some of the radiation is now visible. The hotter the element, the brighter it glows and the more radiant energy it emits.

The key processes in the interaction of a substance with thermal radiation are:

- **Absorption** - the process by which radiation enters a body and becomes heat
- **Transmission** - the process by which radiation passes through a body
- **Reflection** - the process by which radiation is neither absorbed or transmitted through the body; rather, it bounces off

Objects receive thermal radiation when they are struck by electromagnetic waves, thereby agitating the molecules and atoms. More agitation means more energy and a higher temperature. Energy is transferred to one body from another without contact or a transporting medium such as air or water. In fact, thermal radiation heat transfer is the only form of heat transfer possible in a vacuum.

Typical units of measure for rate of radiant heat transfer: Watts per square meter (W/m^2)

The radiation of heat can be described by the reference to the so-called **'black' body**.

2.5.3.1 The Black Body (Ref. The Engineering Toolbox, http://www.engineeringtoolbox.com/36_431.html)

A black body is defined as a body that absorbs all radiation that falls on its surface. Actual black bodies don't exist in nature - though its characteristics are approximated by a hole in a box filled with highly absorptive material. The emission spectrum of such a black body was first fully described by Max Planck.

The energy radiated by a **blackbody** is proportional to the fourth power of the absolute temperature and is given by **Stefan-Boltzmann Law:**

$q = \sigma T^4 A$
where
q = heat transfer (W)
σ = 5.6703 10^{-8} ($W/m^2.K^4$) - **The Stefan-Boltzmann Constant**
T = absolute temperature Kelvin (K)
A = area of the emitting body(m^2)

A black body is a hypothetic body that completely absorbs all wavelengths of thermal radiation incident on it. Such bodies do not reflect light, and therefore appear black if their temperatures are low enough so as not to be self-luminous. All blackbodies heated to a given temperature emit thermal radiation.

2.5.3.2 Emissivity Coefficient

For objects other than ideal blackbodies the **Stefan-Boltzmann Law** can be expressed as:

$q = \varepsilon \sigma T^4 A$
where
ε = emissivity of the object (= 1 for a black body)

The emissivity lies in the range $0 < \varepsilon < 1$ and depends on the type of material and the temperature of the surface. The emmisivity of some common materials are:

- oxidized Iron at 390 ^oF (199 ^oC) - $\varepsilon = 0.64$
- polished Copper at 100 ^oF (38 ^oC) - $\varepsilon = 0.03$
- emmissivity coefficients for other materials

2.5.3.3 The Net Radiation Loss Rate

If a hot object is radiating energy to its cooler surroundings, the net radiation loss rate can be expressed as:

$q = \varepsilon \sigma (T_h^4 - T_c^4) A$
where
T_h = hot body absolute temperature
T_c = cold surroundings absolute temperature

2.5.4 The Impact of Insulation (Ref. Core Training Program, Module 8, SIEMP)

Insulation is used in buildings and in manufacturing processes to prevent heat loss or heat gain. Although its primary purpose is an economic one, it also provides more accurate control of temperatures in the conditioned space. It also prevents condensation on cold surfaces and the resulting corrosion.

The most significant analysis of insulation involves determination of economical thickness. As in most engineering decisions, it is a trade-off between the insulation cost and the value of energy saved. The first step should be to eliminate all bare surfaces, hot or cold, by providing the optimum amount of insulation.

Exposure to moisture is perhaps the factor most often missed in the selection and maintenance of an insulating system. To understand the importance of moisture in the insulation, it is helpful to keep in mind that:

- insulation saturated with water transfers heat approximately 15 to 20 times faster than dry insulation

- insulation which is saturated with ice transfers heat approximately 50 times faster than dry insulation.

These relative factors make it clear that critical attention must be paid to vapour barrier selection, installation and maintenance.

Insulation is the energy stabilizer - it keeps the wanted energy in and the unwanted energy out. It protects, controls and saves.

The purpose of any insulating material is to retard heat flow. To calculate the flow of heat through conducting or insulating material the following equation can be used:

$$Q = \frac{\Delta T \times A}{(R + R_s)}$$

where:

Q	=	*heat flow (Wh/h or W)*
ΔT	=	*temperature difference across the medium (^oC)*
A	=	*surface area (m^2)*
R_s	=	*surface resistance ($m^{2o}C/W$)*
R	=	*thermal resistance ($m^{2o}C/W$) = t/k* where t = material thickness (m)

Thermal resistance "R" is defined as the opposition to the passage of heat through the medium or in this case, through the insulating material.

Thermal conductivity "k", on the other hand, is used to express the quantity of heat which will flow across a unit area with the temperature difference of 1 ^oC. (Units are W/m ^oC)

Surface Resistance "R_s" is the opposition to heat flow through the boundary layer between the insulation and the ambient air. The level of resistance provided by this surface film depends on the amount of heat flow through the layer. The R_s value can be determined from Figure 2.7.

Note that the heat flow (Q) depends on the surface resistance (Rs). From Figure 2.7, we see that Rs depends on Q. Therefore, a trial and error solution must be used to determine final Rs and Q values.

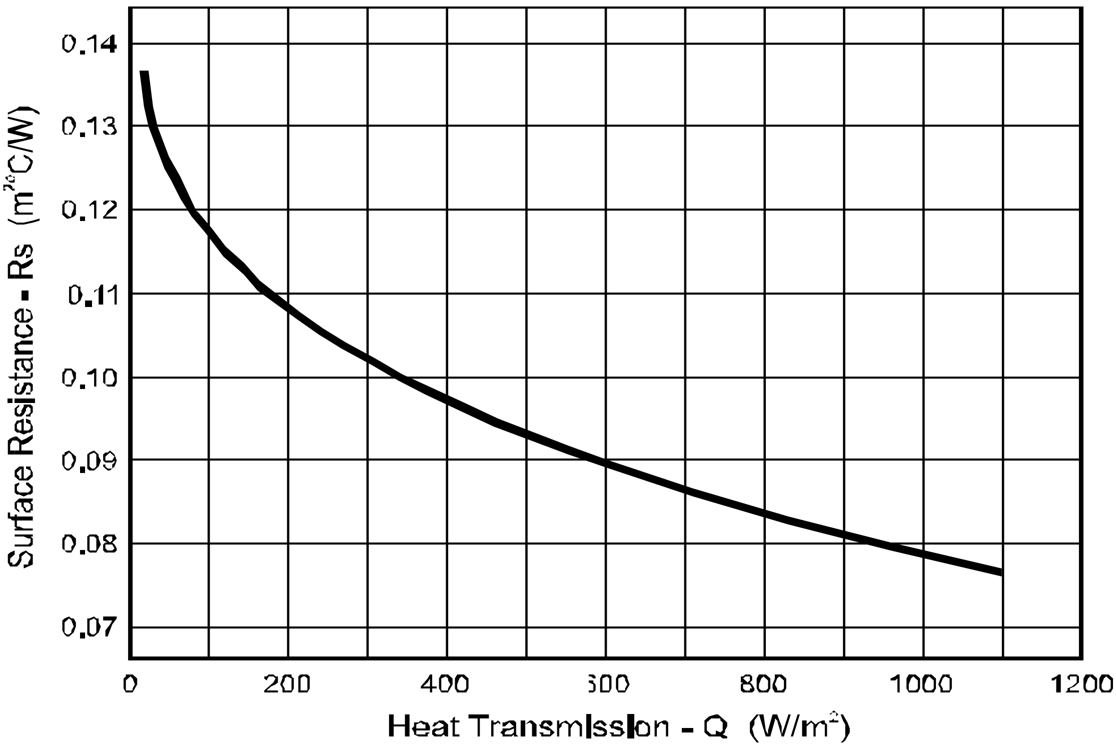


Figure 2.7
HEAT TRANSMISSION vs SURFACE RESISTANCE

2.5.5 Insulation Systems

When contemplating the insulation of equipment, mechanical systems or buildings, it is helpful to think of an insulation system as having the following three components:

- Insulating material
- Protective covering or finish
- Accessories to secure, fasten, support and seal the insulation.

These components must be compatible for the insulation to function properly.

2.5.5.1 Insulating Materials

Types and Forms of Insulation

Type indicates composition and internal structure, while ***form*** implies overall shape or application.

Types are normally subdivided into the following three groups:

- ***Fibrous insulation*** is composed of small diameter fibres which finally divide the air space. The fibres may be parallel or perpendicular to the surface being insulated and they may be separated or bonded together. Glass, rock wool, slag wool and alumina silica fibres are used. Glass fibre and mineral wool are the most widely used insulations of this type.

- ***Cellular insulation*** is composed of small individual cells separated from each other. The cellular material may be glass or foamed plastic such as polystyrene, polyurethane and elastomeric

- ***Granular Insulation*** is composed of small nodules which contain voids or hollow spaces. It is not considered the true cellular material since gas can be transferred between the individual spaces. This type can be produced as a loose pourable material, or combined with a binder and fibres to make a rigid insulation.

Insulation is produced in variety of forms suitable for specific functions and applications. The combined form and type of insulation determines the proper method of insulation. The forms most widely used are:

- ***Rigid board*** comes in blocks, sheet and preformed shapes. Cellular and granular insulations are produced in these forms.

- ***Flexible sheet*****,** and preformed shapes. Cellular and fibrous insulations are produced in these forms.

- ***Flexible blankets***. Fibrous insulations are produced in flexible blankets.

- ***Cement*** (insulating and finishing). Produced from fibrous and granular insulations and cement. They may be of the hydraulic air setting or air drying types.

Major Insulating Materials

The following is a general inventory of the characteristics and properties of major insulating materials used in Industrial, Commercial and Institutional installations.

- ***Calcium Silicate*** is a granular insulating material made of lime and silica, reinforced with organic and inorganic fibres and moulded into rigid forms. The temperature range covered is from 38 to 982 ^{o}C. Flexural strength is good. Calcium Silicate is water absorbent. However, it can be dried out without deterioration. The material is noncombustible and used primarily on hot piping and surfaces. Jacketing is generally field applied.

- ***Cellular Elastomeric insulation*** is composed principally of natural and synthetic elastomers, or both, processed to form a flexible, semi-rigid or rigid foam with predominantly closed cell structure. Upper temperature limit is 104^{o}C***.***

- ***Cellular glass*** is fabricated into boards, pipe covering and other shapes. The service temperatures range from -40 to 482 ^{o}C. This material has a low thermal conductivity at low temperatures, low abrasion resistance, good resistance to substrate corrosion, and good sound absorption characteristics.

- ***Fibrous glass*** is manufactured in variety of forms including flexible blankets, rigid and semirigid boards and pipe covering. Service temperature range from -73 to 538 ^{o}C depending on binder and structure.

- ***Foam plastic insulations*** are predominantly closed cellular rigid materials. Thermal conductivity may deteriorate with time due to aging because of the air diffusing into the cells. Foamed plastics are generally used in lower and intermediate temperature ranges.

- ***Mineral fibre and mineral wool*** are produced by bonding rock and slag fibres with heat resistant binder. The upper service temperature limit can reach 982 ^{o}C. The material is noncombustible and is used in high and intermediate temperature ranges less than 200 ^{o}C.

- ***Refractory fibre insulations*** are mineral and ceramic fibres, including alumina and silica, bound with extremely high temperature binders. They are manufactured in blanket or rigid brick form. Thermal shock resistance and temperature limits are high (up to 1000 °C).

Common insulating materials are summarized in Table 2.1. Table 2.2 presents the properties of common insulation types.

Table 2.1
BASIC TYPES OF INSULATION

Type	Form	Temp. Range	k-Factor *	Notes
Calcium Silicate	Pipe Covering Block Segments	up to 982°C	.066 at 150°C	Good mechanical abuse characteristics, non-combustible. Some are water absorbent.
Cellular Glass	Pipe Covering Block Segments	-267°C to 482°C	.077 at 150°C	Good strength, water and vapour resistant, non-combustible. Poor abrasion resistance.
Glass Fibre	Pipe Covering Board Blanket	to 455°C to 510°C	.035 at 24°C .050 at 150°C (varies, see manf. data)	Properties variable. Good handling and workability. May be water absorbent. Some are non-combustible.
Mineral Fibre	Pipe Covering Board	to 870°C	.035 at 24°C .061 at 150°C (conductivity varies with density)	Non-combustible, good workability, water absorbent.
Ceramic Fibre	Blanket or Board	to 1760°C	.30 at 93°C	Temperature range varies with manufacturer, style and type.
Cements	Hydraulic setting cement High temperature mineral wool Pointing and finishing cement (Mineral or Vermiculite)	to 650°C to 1040°C to 760°C	1.75 at 315°C .69 at 315°C .55 at 93°C	One coat application - Insulating and finishing. Slow drying, rough texture - filling and insulating. Used over basic insulation - smooth finish, usually 3.175 mm to 6.35 mm thick application.

** k-Factor = W/(m °C)*

Table 2.2
THERMAL PROPERTIES OF TYPICAL BUILDING & INSULATING MATERIALS - DESIGN VALUES

Description	Density (kg/cu.m)	Conductivity k (W/mC)	Conductance C (W/sq.mC)	Resistance (R) Per meter thickness 1/k (mC/W)	Resistance (R) For listed thickness 1/C (sq.m.C/W)	Specific Heat (Cp) (kJ/kgC)
INSULATING MATERIALS						
Blanket & Batt						
Mineral Fiber, fibrous form processed from rock, slag, or glass						
approx. 75_100 mm	4.8_32.0	__	0.52	__	1.94	
approx. 90 mm	4.8_32.0	__	0.44	__	2.29	
approx. 140_165 mm	4.8_32.0	__	0.30	__	3.34	
approx. 150_175 mm	4.8_32.0	__	0.26	__	3.87	
approx. 215_230 mm	4.8_32.0	__	0.19	__	5.28	
approx. 305 mm	4.8_32.0	__	0.15	__	6.69	
Board & Slabs						
Cellular Glass	136	0.050	__	19.85	__	0.75
Glass fiber, organic bonded	64 _ 144	0.036	__	27.76	__	0.96
Expanded perlite, organic bonded	16.0	0.052	__	19.29	__	1.26
Expanded rubber (rigid)	72.0	0.032	__	31.58	__	1.68
Expanded polystyrene extruded						
Cut cell surface	28.8	0.036	__	27.76	__	1.22
Smooth skin surface	28.8 _ 56.0	0.029	__	34.70	__	1.22
Expanded poly tyrene, molded beads	16.0	0.037	__	27.03	__	__
	20.0	0.036	__	27.76	__	__
	24.0	0.035	__	28.94	__	__
	28.0	0.035	__	28.94	__	__
	32.0	0.033	__	30.19	__	__
Cellular polyurethane (R_11 exp)(unfaced)	24.0	0.023	__	43.38	__	1.59
Foil_faced, glass fiber_reinforced cellular Polyisocyanurate (R_11 exp)	32.0	0.020	__	49.97	__	0.92
Nominal 13 mm		__	1.59	__	0.63	
Nominal 25 mm		__	0.79	__	1.27	
Nominal 50 mm		__	0.40	__	2.53	
Mineral fiber with resin binder	240	0.042	__	23.94	__	0.71
Mineral fiberboard, wet felted						
Core or roof insulation	256 _ 272	0.049	__	20.40	__	
Acoustical tile	288	0.050	__	19.85	__	0.80
Acoustical tile	336	0.053	__	18.74	__	
Mineral fiberboard, wet molded						
Acoustical tile	368	0.060	__	16.52	__	0.59
Wood or cane fiberboard						
Acoustical tile (13 mm)	__	__	4.54	__	0.220	1.30
Acoustical tile (19 mm)	__	__	3.01	__	0.330	__
Interior finish (plank, tile)	240	0.050	__	19.85	__	1.34
Cement fiber slabs (shredded wood with Portland cement binder)	400 _ 432	0.072_0.070	__	13.88 _ 13.12	__	__
Cement fiber slabs (shredded wood with magnesia oxysulfide binder)	352	0.082	__	12.15	__	1.30
FIELD APPLIED						
Polyurethane foam	24.0 - 40.0	0.023-0.026	--	43.38 - 36.50	--	
Spray cellulose fiber base	32.0 - 96.0	0.035-0.043	--	23.11 - 28.94	--	

2.5.5.2 Protective Coverings and Finishes

The efficiency and service of insulation is directly dependant upon its protection from moisture entry and mechanical or chemical damage. Choices of jacketing and finish materials are based upon the mechanical, chemical, thermal and moisture conditions of the insulation, as well as cost and appearance.

Protective coverings are divided into six functional types.

- ***Weather barrier*** - the basic function of the weather barrier is to prevent entry of water. If water is deposited within the insulation, its insulating properties will be significantly reduced. Applications consist of either a jacket of metal or plastic or a coating of weather barrier mastic.

- **Vapour retarders -** are designed to retard the passage of moisture vapour from the atmosphere to the surface of the insulation. Joints and overlaps must be sealed with a vapour tight adhesive or sealer. Vapour retarder are available in three forms:

  - **Rigid jacketing** reinforced plastic, aluminum or stainless steel fabricated to exact dimensions and sealed vapour tight.

  - **Membrane jacketing** metal foils, laminated foils or treated paper which are generally factory applied to the insulating material.

  - **Mastic applications**, either emulsion or solvent type, which provide a seamless coating but require time to dry.

- **Mechanical abuse covering -** metal jacketing provides the strongest protection against mechanical damage from personnel, equipment and machinery. The compression strength of the insulation material should also be considered when assessing mechanical protection**.**

- **Low flame spread and corrosion resistant coverings -** when selecting material for potential fire hazard areas, the insulation material and the jacketing must be considered as a composite unit. Most of the available types of jacketing and mastic have low flame spread rating. This information can usually be obtained from manufacturer's data.

Stainless steel is the most successful in resisting the corrosive atmosphere, spills and leaks. Mastics are also generally resistant to corrosive atmospheres.

- **Appearance coverings and finishes -** various coatings, finishing cements, fitting covers and jackets are chosen primarily for their appearance value in exposed areas. Typically for piping, jacketed insulation is covered with a reinforcing canvas and coated with a mastic to give it a smooth even finish.

- **Hygienic coverings -** coatings and jackets must present a smooth surface which resists fungal and bacterial growth, especially in food processing areas and hospitals. High temperature steam or high pressure water wash down conditions require jackets with high mechanical strength and temperature rating.

2.5.5.3 Accessories

The term accessories is applied to the devices or materials serving one or more of the following functions:

- ***Securement*** of the insulation or jacketing.
- ***Insulation reinforcement*** for cement and mastic
- ***Water flashing***
- ***Stiffening* -** metal lath and wire netting can be applied on high temperature surfaces before insulation is applied
- ***Sealing and caulking***
- ***Expansion and contraction compensation* -** manufactured overlapping or slip joints; bedding compounds and flexible sealers.

2.5.6 Controlling Radiative Heat Transfer

All bodies emit a certain amount of radiation. The amount depends upon the body's temperature and nature of its surface. Some bodies only emit a small amount of radiant energy for their temperature, commonly called low emissivity materials (abbreviated low-E). Low-E windows are used to control the heat radiation in and out of buildings. Windows can be designed to reflect, absorb and transmit different parts of the sun's radiant energy.

The condition of a body's surface will determine the amount of thermal radiation that is absorbed, reflected or re-emitted. Surfaces that are black and rough, such as black iron, will absorb and re-emit almost all the energy that strikes them. Polished and smooth surfaces will not absorb, but reflect, a large part of the incoming radiant energy.

The control of radiative heat transfer is therefore largely a matter of materials selection. Tables 2.3 and 2.4 provide, respectively, emissivity coefficients and radiation constants for various materials.

Table 2.3: Emissivity Coefficients for Various Materials

Surface Material	Emissivity Coefficient
Aluminium Oxidised	0.11
Aluminium Polished	0.05
Aluminium Anodised	0.77
Aluminium Rough	0.07
Asbestos Board	0.94
Black Body Matt	1.00
Brass Dull	0.22
Brass Polished	0.03
Brick Dark	0.9
Concrete	0.85
Copper Oxidised	0.87
Copper Polished	0.04
Glass	0.92
Plaster	0.98
Tile	0.97
Water	0.95
Wood Oak	0.9
Paint	0.96
Paper	0.93
Plastics	0.91 Av
Rubber Nat Hard	0.91
Rubber Nat Soft	0.86
Steel Oxidised	0.79
Steel Polished	0.07
Stainless Steel Weathered	0.85
Stainless Steel Polished	0.15
Steel Galvanised Old	0.88
Steel Galvanised New	0.23

Table 2.4: Radiation Constants for Various Materials

Product	Radiation Constant x 10^{-8} W/m^2 ^{o}C^4
Black body	5,7
Brass, dull	0,152
Brick	5,16
Cast iron, rough oxidized	5,09
Copper, polished	0,119
Cotton	4,23
Glass	5,13
Lamp black	5,16
Oil paint	4,30
Paper	4,43
Plaster	5,16
Sand	4,20
Shavings	4,10
Silk	4,30
Silver	1,19
Tin	0,26
Water	3,70
Wood	4,17
Wool	4,30
Wrought iron, dull oxidised	5,16
Wrought iron, polished	1,55
Zinc, dull	0,152

Radiation constant is the product $\varepsilon\,\sigma$
where
σ = 5.6703 10^{-8} (W/m^{2}K^4) **Stefan-Boltzmann Constant**
ε = emissivity of the object (= 1 for a black body).

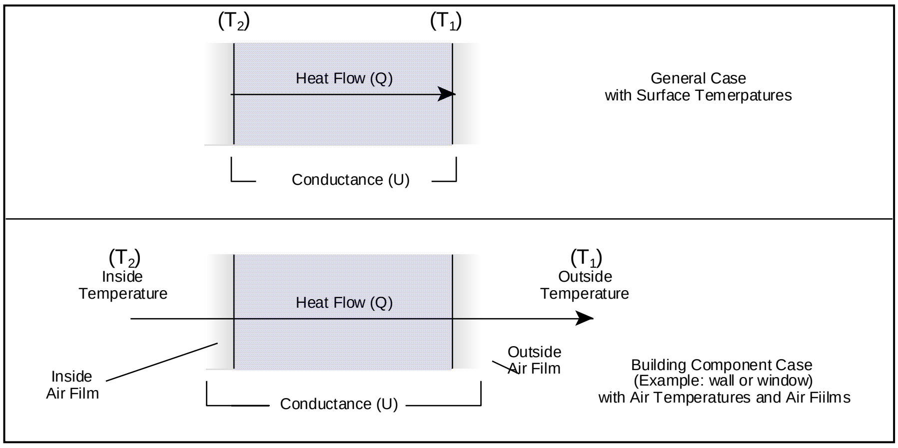
The Radiation constant is used in the equation given in Section 2.5.3.3 to calculate the net radiation heat loss.

2.6 Energy Estimation Calculations

2.6.1 Conductive Heat Flow

Heat transfer by conduction occurs through the walls, roof and windows of building. As illustrated below, heat is transferred or conducted from the warmer side of the material to the cooler side.

The nature of the material or materials between the two extremes of temperature determines the conductance. It is common to refer to the insulating value or "R-value" of the material rather than its conductance. In the metric system, this is called the "RSI-value." (Thermal resistance and thermal conductance are related. One is the reciprocal of the other.)



Note: $T_2 > T_1$ in the above configurations

Figure 2.8 - Heat Transfer by Conduction

This estimation method can be used with any flat surface if the two temperatures accurately represent the surface temperature of the material through which the heat is being conducted.

Table 2.5: Heat Transfer Parameters

Parameter	Symbol	Units	Sample	Method of Determination
Conductance	U	$W/m^2\,^OC$	0.9 $W/m^2\,^OC$	See below
Surface Area	A	m^2	100 m^2	Measurement
Higher Temperature	T_2	^OC	20^OC	Measurement, estimation
Lower Temperature	T_1	^OC	5^OC	Measurement, estimation
Time	t	hours	n/a	Estimation, calculation
Heat Flow	Q	kW	1.35 kW	Formula below.

Conductance . . . Thermal *conductivity* is a measure of the ability of a material to conduct heat across a material in the presence of a temperature difference on either side of the material. It is customarily expressed as heat flow per unit of material thickness per degree of temperature difference. Units are W/m^OC (SI). More commonly, for a given thickness of material, the *conductance* of the material is specified in heat flow per unit surface area per degree of temperature difference. Units of *conductance* are $W/m^{2O}C$ (SI).

The resistance to heat flow per unit of thickness, or per unit area for a specific thickness is commonly termed the “RSI-value” in SI units and the "R-value" in imperial units. The "R" and "RSI" values are the inverse of the conductivity and the conductance respectively. SI units are m^OC/W and $m^{2O}C/W$ respectively.

The conductance of an *assembly* of materials (layers) is often referred to as the "transmittance".

Temperature . . . In some circumstances, it is possible to substitute air temperatures for the surface temperatures T_2 and T_1. This is commonly done in the case of building components such as walls, roofs, and windows, where the insulating effect of the air layer adjacent to the inside and outside surfaces is taken into account.

Equation for rate of heat transfer:

$Q = U \times A \times (T_2 - T_1)$ in units of watts (W).

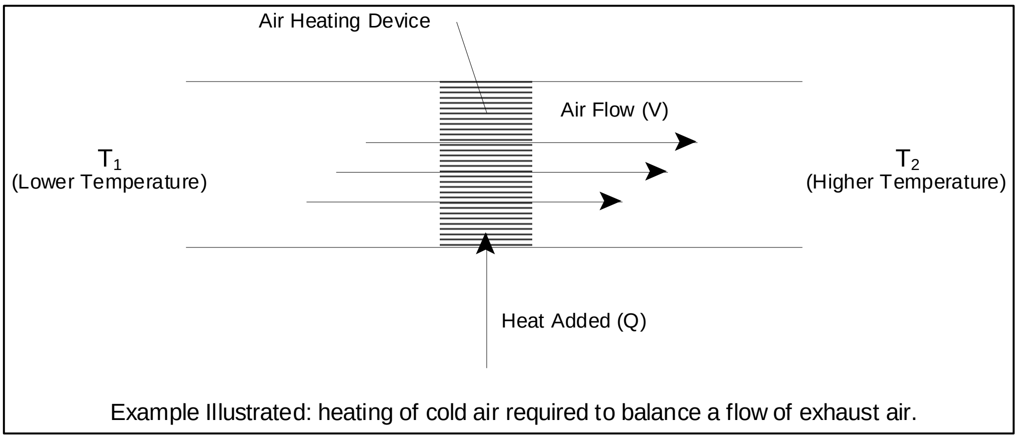


Figure 2.9: Air flow with sensible heat

Total heat transferred:

Heat = Q x t/1000 in units of kilowatt-hours (kWh)
Heat = Q x t x 3600 in units of joules (J)

Assumption and Cautions

- Significant variation in temperatures over time will reduce accuracy.
- The temperature does not vary across the surface area involved.
- Temperatures used must be surface temperatures if conductances do not include allowance for air films.

2.6.2 Convective Heat Flow - Sensible

This type of forced convective energy flow is common in the heated or cooled air streams that provide ventilation and exhaust in buildings.

This estimation method only considers the sensible heat in the air and the moisture contained in the air, but does not take into account possible changes in moisture content of the air due to condensation or evaporation. Various facility energy flows are represented by the following situations:

- Heat loss when warm air flows to a cooler environment. An example would be warm exhaust air in winter.
- Heat required to raise temperature of cold air entering a warm environment. An example would be cold air intake in the heating season.
- The heat gained (and hence requirement for cooling) when warm air is drawn into a cool environment. An example would be warm air intake into an air conditioned building in the cooling season.

Table 2.6: Convective Sensible Heat Loss Parameters

Parameter	Symbol	Units	Sample	Method of Determination
Air Flow Rate	V	L/s	1,800 l/s	Measurement, estimation
Inside/Outside Temperature	T_2	^{O}C	$20^{O}C$	Measurement, estimation. See note below.
Outside/Inside Temperature	T_1	^{O}C	$5^{O}C$	Measurement, estimation See note below.
Time	t	hours	n/a	Estimation, calculation
Heat Flow	Q	kW	33.3 kW	Formula below.

Equation for rate of heat transfer:

$Q = V \times (T_2 - T_1) \times 1.232$ in units of watts (W).

Total heat transferred:

Heat = Q x t/1000 in units of kilowatt-hours (kWh)
Heat = Q x t x 3600 in units of joules (J)

Assumptions and Cautions

- The relative humidity of the air involved is 50% at a temperature of $21^{O}C$. The constant 1.232 takes these conditions into account.
- This method should not be used for very high temperature and high humidity air flows. It is primarily intended for building heating and cooling calculations.
- For any given air flow into a building there is a balancing outflow, either by fan system, vents, or ex-filtration through the structure. The reverse is also true. In the ***Energy Outflow Inventory***, only account for the energy needed to heat the incoming stream or lost in the outgoing stream. Accounting for both would be double accounting.

2.6.3 Convective Heat Flow - Latent

This type of energy flow is found in heated or cooled moist air streams such as commercial building ventilation and exhaust systems.

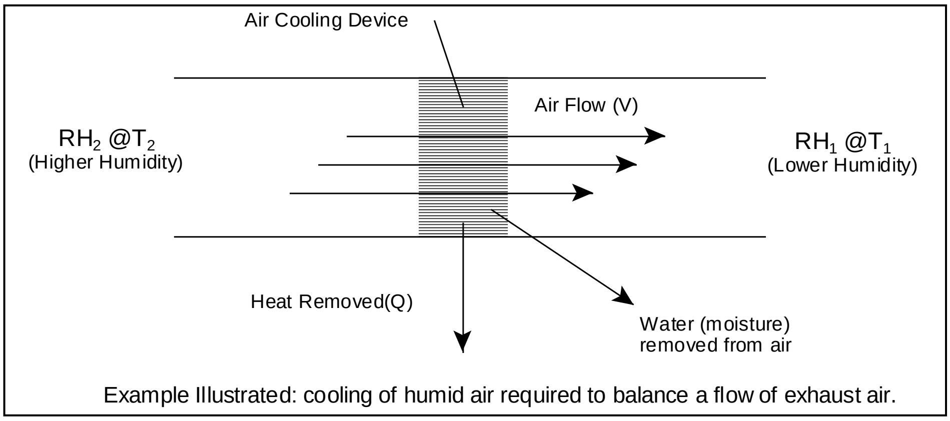


Figure 2.10 - Air Flow with Latent Heat

This energy flow accounts for condensation or evaporation that may take place as a result of temperature and humidity changes associated with the air flow. It does not take into account the sensible heat involved in the air flow. Depending on the humidity difference, two types of facility energy flows are represented by the following situations:

- Heat gain (need for cooling) when water condenses (or is removed) from humid air. This may be associated with the cooling by an air conditioning system of outside air supply stream during the summer.

- Heat required to humidify (add moisture to) dry air by evaporation. An example would be the humidification of outside ventilation air intake during the winter.

Table 2.7: Convective Latent Heat Loss Parameters

Parameter	Symbol	Units	Sample	Method of Determination
Air Flow Rate	V	L/s	1,831L/s	Measurement, estimation
Temperature (Dry Bulb)	T_1	^{O}C	$24^{O}C$	Measurement, estimation
Lower Relative Humidity	RH_1	%	50%	Measurement, estimation (see Thermal Basics section)
Temperature (Dry Bulb)	T_2	^{O}C	$31^{O}C$	Measurement, estimation
Higher Relative Humidity	RH_2	%	50%	Measurement, estimation (see Thermal Basics section)
Humidity Factor (High)	H_2	g/kg	14.5 g/kg	Humidity measurement and chart. See details below.
Humidity Factor (Low)	H_1	g/Kg	9 g/kg	Humidity measurement and chart. See details below.
Time	t	hours	n/a	Estimation, calculation
Heat Flow	Q	kW	30.3 kW	Formula below.

Determining the Humidity Factor . . . At any given humidity and temperature, the air will hold a certain amount of moisture. This is customarily measured in terms of the number of grams of water per kilogram of dry air (air with 0% relative humidity). A Psychrometric Chart is used for determining the *humidity factor,* given the dry bulb temperature (T_1 or T_2) and the humidity (RH_1 or RH_2).

Equation for rate of heat transfer:

$Q = V \times (H_2 - H_1) \times 3.012$ in units of watts (W).

Total heat transferred:
Heat = Q x t/1000 in units of kilowatt-hours (kWh)
Heat = Q x t x 3600 in units of joules (J)

Assumption and Cautions

- This estimation method is intended primarily for building heating and cooling purposes. It should not be used for situations involving extremely high temperatures and humidity. Typical conditions are assumed in determining the factor 3.012.

- For any given air flow into a building, there is a balancing outflow, either by fan system, vents, or ex-filtration through the structure. The reverse is also true. In the ***Energy Outflow Inventory***, account only for the energy needed to heat the incoming stream, or lost in the outgoing stream, as accounting for both would constitute double accounting.

2.6.4 Hot or Cold Fluid

Fluid flows at various temperatures are common in various processes. Water is commonly used to move heat, either deliberately or coincidentally.

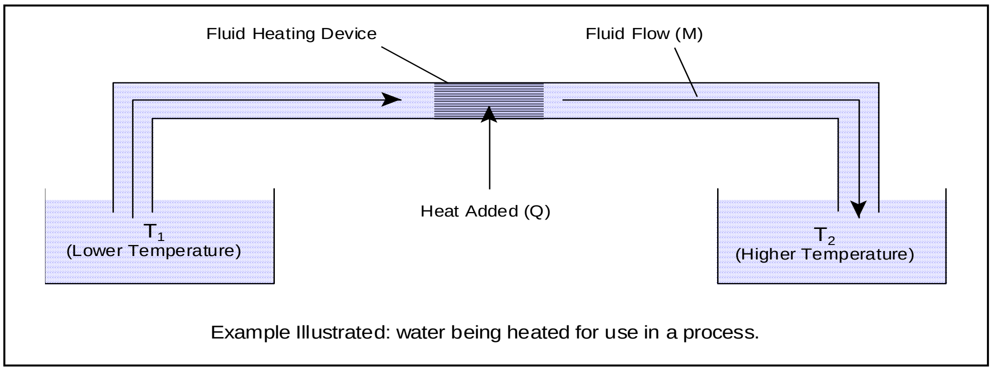


Figure 2.11 - Thermal Energy in a Hot or Cold Fluid

This method of estimating can be used for a number of purposes including:

- To determine heat lost in an flow of hot fluid.
- To determine the heat required to heat a stream of cold fluid.
- To determine the amount of cooling required to reduce a fluid temperature.

Table 2.8: Fluid Heat Transfer Parameters

Parameter	Symbol	Units	Sample	Method of Determination
Mass Flow Rate	M	kg/s	0.35 kg/s	Measurement, estimation
Higher Temperature	T_2	^{O}C	40^{O}C	Measurement, estimation.
Lower Temperature	T_1	^{O}C	10^{O}C	Measurement, estimation
Heat Capacity (Specific Heat) of Fluid	C	kJ/ kg^{O}C	4.2 kJ/kg^{O}C	Technical reference, or table in Thermal Basics module.
Time	t	hours	n/a	Estimation, calculation
Heat Flow	Q	kW	44.1 kW	Formula below.

Higher and Lower Temperature . . . When using this method to estimate energy flows, the lower temperature is typically assumed to be the temperature of the fluid which entered the facility. For water, this might be the intake water temperature.

In heating circumstances, the lower and higher temperatures are simply taken as the “from” and “to” temperatures respectively. For cooling, the values are reversed.

Mass Flow Rate . . . The mass flow rate is related to the fluid volume flow rate by the density. Standard SI units of density are kilograms per cubic metre (kg/m^3) in SI and pounds per cubic foot (lb/ft^3) in Imperial measurement. Flow rates are often given in litres per second l/s. It is therefore necessary to knowing the density of a substance in kg/l. Water is 1.0 kg/l. The mass flow rate would be:

Mass Flow Rate = Volume Flow (l/s) x Density (kg/l)

Equation for rate of heat transfer:

$Q = M \times (T_2 - T_1) \times C \times 1000$ in units of watts (W).

Total heat transferred:

Heat = Q x t/1000 in units of kilowatt-hours (kWh)
Heat = Q x t x 3600 in units of joules (J)

Assumption and Cautions

Ensure that the lower or reference temperature is determined in consideration of the usefulness of the thermal energy as discussed in the Energy Basics module.

2.6.5 Pipe Heat Loss

Pipes carrying fluid will incur a heat loss or heat gain depending upon the relative temperatures inside and outside the pipe. Heat loss from a pipe must be treated differently than from a flat surface because of the geometry of a round pipe.

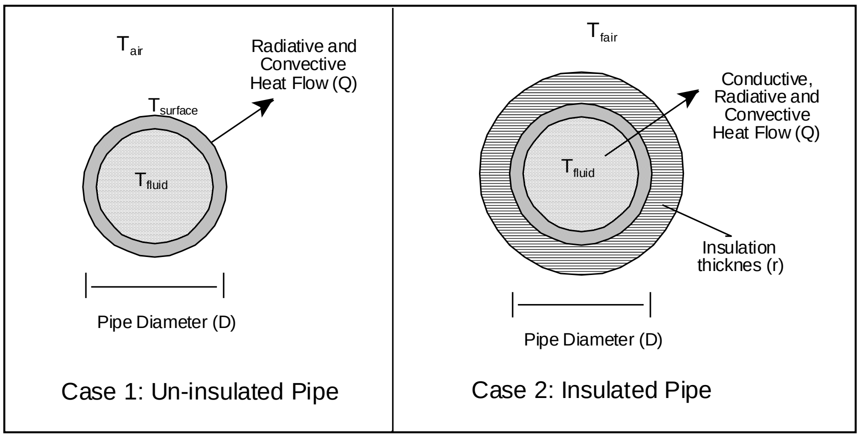


Figure 2.12 - Pipe Heat Loss

This heat loss estimation method is simplified. It is based on the fluid temperature (and assumed surface temperature for the bare pipe) and an assumed surrounding air temperature of approximately 20^{O}C. The heat mechanism is a combination of conductive, convective, and radiative.

Table 2.9: Pipe Heat Loss Parameters

Parameter	Symbol	Units	Sample	Method of Determination
Fluid (interior) Temperature or Surface Temp.	T_f T_s	^{O}C	150^{O}C Bare Surface	Measurement, estimation - use pipe temperature for bare or un-insulated pipes.
Pipe Diameter	D	in. NPS	3" NPS	Measurement
Pipe Length	L	m	20 m	Measurement
Heat Loss Factor	F	W/m	575 W/m	See note below.
Insulation Thickness	r	mm	nil	If present, thickness is in millimetres.
Time	t	hours	n/a	Estimation, calculation
Heat Flow	Q	kW	11.5 kW	Formula below.

Heat Loss Factor . . . Tables are available to provide data that, along with the fluid temperatures (or pipe temperatures) and pipe diameter, provide values for the heat-loss factor in watt-hours per hour per metre of pipe. This is the same as watts per metre (W/m) of pipe.

Pipe heat loss tables give data for bare pipe and insulated pipe, for various thicknesses of common insulating materials.

Equation for rate of heat transfer (Loss):

Q = F x L	in units of watts (W).

Total heat transferred:

Heat = Q x t/1000	in units of kilowatt-hours (kWh)
Heat = Q x t x 3600	in units of joules (J)

Assumptions and Cautions

- The temperature surrounding the pipe is 21.1^{O}C for bare pipes, and 18^{O}C for the case of insulated pipe.
- The pipe is bare steel or steel insulated with the materials specified in the tables.
- If the pipe is outside a building, then the heat lost from it will definitely be a facility outflow. However, if the pipe is inside the building, the heat may contribute to general building heating (or overheating in some cases). In this case the heat lost from the pipe is not, itself, a facility outflow.

2.6.6 Refrigeration

Refrigeration systems are designed and operated to move heat. It is often useful in an energy flow inventory, or during assessment of the opportunities for heat recovery, to be able to estimate the quantity of heat rejected by a refrigeration system per unit time.

The heat rejected by a refrigeration system is primarily the heat rejected at the condenser.

The magnitude of this rejected heat is the sum of the electrical energy being supplied to the compressor and the heat being pumped from the evaporator. If this is a water-cooled condenser, the method described previously for a flow of heated fluid could be used. Likewise, for air cooled condensers, the air flow method for sensible heat may be used. If the unit has an evaporative cooling tower, it may be necessary to take into account the latent heat in the air that removes heat from the condenser.

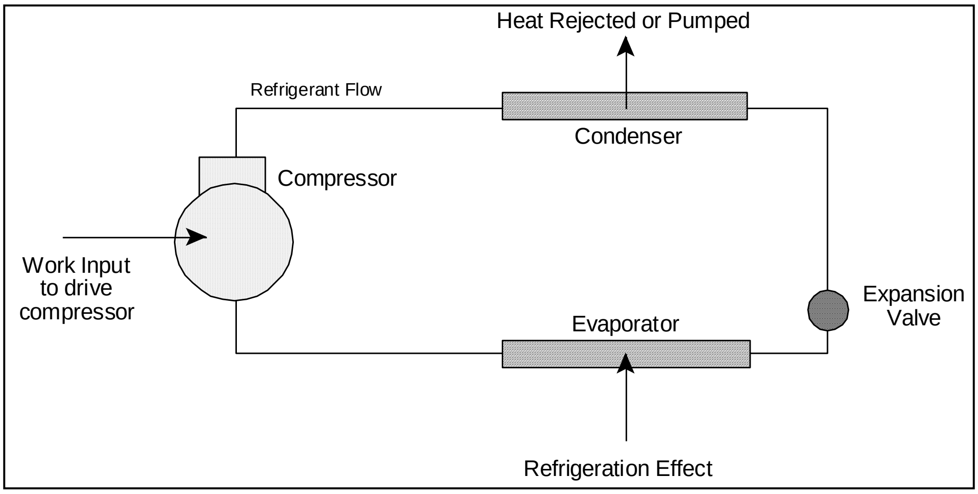


Figure 2.13 - Heat Flow in a Refrigeration System or Heat Pump

Alternatively, a rough approximation could be made based upon the system's ability to move heat, commonly referred to as the coefficient of performance (COP). For a refrigeration system which is to provide cooling or a refrigeration effect, the refrigerating COP is defined mathematically as:

$$COP_R = \text{Refrigeration Effect} / \text{Work Input}$$

When a refrigeration system's purpose is to heat, as with *heat pumps*, the *heating* COP is of interest. It is:

$$COP_H = (\text{Refrigeration Effect} + \text{Work Input}) / \text{Work Input}$$

From these equations, it is clear that, given the COP and the Work Input (which is commonly the electric power to the compressor), one can calculate the energy moved.

Equation for rate of heat transfer:

Q = COP x Power to Compressor (kW) in units of kilowatts (kW)

Total heat transferred in time t, measure in hours is:

Heat = Q x t	in units of kilowatt-hours (kWh)
Heat = Q x t x 3,600,000	in units of joules (J)

Sample Calculation

A refrigeration system that has an estimated average COP_R of 3.2 is found to be drawing 21 kW of electrical power. The rate of heat transfer is:

$$Q = 3.2 \times 21 \text{ kW} = 67.2 \text{ kW}$$

Accurately determining the COP is a complex task. Furthermore, the COP of a system can vary widely depending upon the operating conditions, equipment design, and type of refrigerant. Operating conditions can vary daily, depending on temperatures. The manufacturers and service companies of refrigeration equipment can provide performance information for systems at various operating conditions.

Assumptions and Cautions

- As this method is at best only a rough approximation, use results with caution.

2.6.7 Steam Leaks, Vents and Flow

Steam is the most common medium of transporting large amounts of thermal energy in commercial and industrial facilities. Steam is generated in the boiler plant from fuel at various pressures dependant on the type of equipment, systems, and processes requiring heat. The steam is then distributed by pipe to various uses, but some energy is lost in the distribution piping.   These losses may be estimated by the pipe-heat loss method given earlier.

Another common loss of steam energy is leaks or venting to atmosphere. The discharge of steam may have a purpose if the steam is contaminated, but it still represents an energy flow and a potential opportunity for heat recovery. The energy lost in a leak or venting of steam can be estimated from the diameter of the leak.

In general if the steam flow, measured in kilograms/hour (kg/hr) is known then the equations given below may be used directly. Common methods of determining steam flow would be from a metering station – at a boiler plant or elsewhere in the distribution system. Steam metering is expensive and not extremely reliable.

If the flow from a leak or vent is unknown the method provided below allows an estimate of the flow based upon easily measured data.

Steam Leak or Vent from a Known Orifice Diameter . . . If the diameter of the leak or orifice through which the steam is flowing is known, then an estimate of the energy flow can be obtained. Imperial and metric units are mixed in this example since tables are given in metric units, and pressures are commonly known in Imperial units.

Table 2.10: Steam Heat Loss Parameters

Parameter	Symbol	Units	Sample	Method of Determination
Steam Pressure	P	psig kPa	75 psig 517 kPa	Measurement, estimation. Note: 1 kPa = 0.145 psi
Orifice Diameter	D	inch	1/4 in.	Measurement, 1 mm = 0.039in.
Steam Flow	M	lb./hr kg/hr	165 lb./hr 75 kg/hr	Lookup in Tables Note: 1 kg/hr = 2.205 lb./hr.
Steam Enthalpy[1]	H	kJ/kg	2747 kJ/kg	Lookup in the column (h_g) for pressure (P) in Steam Table.
Time	T	hours	n/a	Estimation, calculation
Heat Flow	Q	kW	53 kW	Formula below.

Enthalpy of Steam . . . The *enthalpy* of the steam is the total heat contained in the water and the vapour. It is assumed in this method the steam is saturated. This means that it has not been heated beyond the point of turning all the water to a vapour, i.e. it is not superheated.

Equation for rate of heat transfer:

Convert the flow in lb./hr to flow in kg/hr by dividing the number of lb./hr by 2.205.

$Q = M \times h \;/\; 3600$ in units of kilowatts (kW)

Total heat transferred in time t, measure in hours is:

$\text{Heat} = Q \times t$ in units of kilowatt-hours (kWh)
$\text{Heat} = Q \times t \times 3.6$ in units of joules (MJ)

Assumptions and Cautions

- The flow estimation method is only a rough approximation.
- This method does not take into account the enthalpy of the water used to generate the steam – or left in the condensate.

General Cautions

The methods detailed in this section are simple estimation methods and should only be used as a first approximation for energy use in a given situation. They can help identify potential energy saving opportunities, but proper engineering calculations should be used to verify and refine the initial estimates before actually changing the systems involved.

All of the methods above assume static or non-changing conditions over the time period specified. For estimations that may involve monthly or yearly time periods over which conditions change periodically (i.e.: daily, nightly, weekly, or seasonally), it will be necessary to repeat the estimation for a number of shorter time periods over which conditions are assumed to be constant. For example, it may be necessary to estimate exhaust energy-use for day and night periods for each month, taking into account night setback of temperatures, and seasonal changes in outdoor temperatures.

Worksheet 2-1 Sensible and Latent Heat Calculation

Situation: Outside air is drawn into an air conditioned lab area of a hospital to make-up for contaminated air exhausted from the lab area. The exhaust rate is 1000 l/s for 10 hours per day.

Question: How much energy, in MJ, must be removed by the air conditioning system to cool and dry the air to the interior conditions each day?

Exhaust Air Conditions		**Makeup Air Conditions**	
Air Temperature	20^oC	Air Temperature	30^oC
Relative Humidity	50%	Relative Humidity	70%

Method

1. Calculate the net sensible heat flow associated with the make-up air.

   Heat (MJ) = Flow (l/s) x (T_{makeup} - $T_{exhaust}$) x 1.2 x hours x 0.0036

   = ________ x (______ - _______) x 1.2 x 0.0036

   = _________MJ

2. Calculate the moisture content of the two air streams using a psychometric chart; a copy is provided at the end of this Section..

   H_{makeup} = _______ g/kg $H_{exhaust}$ = _______ g/kg

3. Calculate the net latent heat flow associated with the make-up air.

   Heat (MJ) = Flow (l/s) x (H_{makeup} - $H_{exhaust}$) x 3.0 x hours x 0.0036

   = ________ x (______ - _______) x 3.0 x 0.0036

   = _________MJ

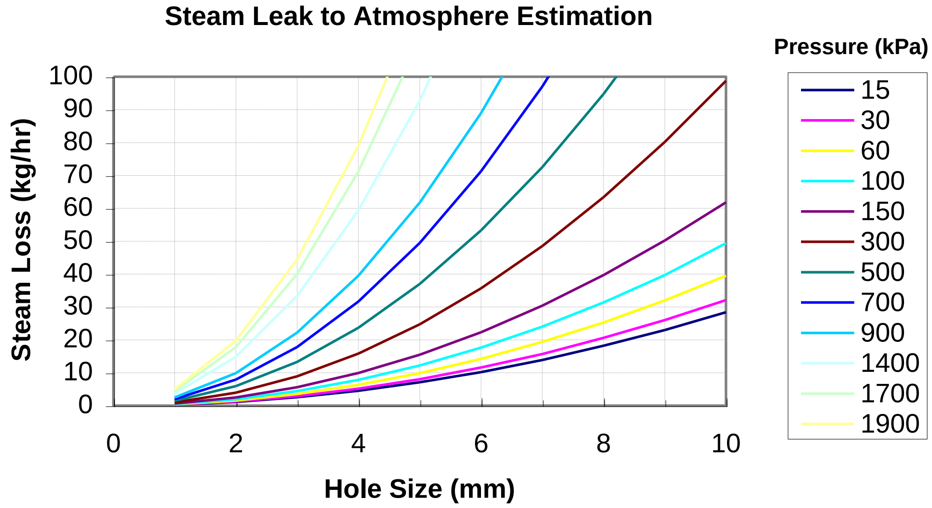
4. Calculate the total heat involved.

   Total Heat = _________ + __________ = _________ MJ/day

Worksheet 2-2 Steam Leak Calculation

1. Estimate the rate of steam leakage using an estimate of the size of the hole and the steam pressure.

   Leak Size: ____ mm Pressure ________ kPa Leakage Rate: _______kg/hr



2. Determine the energy content of the steam at the leak pressure. Assume that the steam is saturated, and use the Steam column in the simple steam table below

   Leak Pressure: _________ kPa Energy Content: ___________ kJ/kg (steam)

Gauge Pressure kPa	Gauge Pressure bar	Absolute Pressure bar	Temperature C	Water kJ/kg	Evap kJ/kg	Steam kJ/kg
15	0.15	1.163	103.9	435.6	2246.7	2682.3
30	0.30	1.313	107.4	450.4	2237.2	2687.6
60	0.60	1.613	113.6	476.4	2220.4	2696.8
100	1.00	2.013	120.4	505.6	2201.1	2706.7
150	1.50	2.513	127.6	536.1	2181.0	2717.1
300	3.00	4.013	143.8	605.3	2133.4	2738.7
500	5.00	6.013	158.8	670.9	2086.0	2756.9
700	7.00	8.013	170.5	721.4	2047.7	2769.1
900	9.00	10.013	180.0	763.0	2015.1	2778.1
1400	14.00	15.013	198.4	845.1	1947.1	2792.2
1700	17.00	18.013	207.2	885.0	1912.1	2797.1
1900	19.00	20.013	212.5	909.0	1890.5	2799.5

3. Calculate the cost of energy loss for steam raised with a boiler efficiency of 80%:

   Power = ________ kg/hr x __________ kJ/kg ÷ 1,000,000 = _______GJ/hr

   = ________ GJ/hr x (1 / 0.8) x R. _______/GJ = R.______/hr